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ATMOSPHERIC TURBULENCE AND AIRPLANE RESPONSE IN CONVECTIVE-TYPE CLOUDS

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Summary

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Measurements of atmospheric turbulence obtained from airplane flights through cumulus clouds and thunderstorms are reviewed. Time histories of the vertical and lateral components of true gust velocities are considered in order to indicate the irregular nature of the velocity fluctuations for a large range of wavelengths. Spectra of turbulence and root-mean-square gust velocities are used to compare the turbulence intensities of several meteorological conditions and the variation within a given storm. Flight measurements of the airplane motions and displacements are evaluated to show the altitude deviations, the vertical accelerations, and the attitude variations during traverses of severe storms.

Introduction

The occurrence of severe storms along the airways constitutes one of the important conditions that must be contended with in air traffic control. The conventional traffic control problems such as those relating to airplane separation enroute, to holding and to approach procedures are intensified by the occurrence of severe storms. Closely allied problems such as piloting difficulties, passenger distress, and airplane stability and structural loading considerations also arise because of the severe flight conditions encountered. Such flight conditions include poor visibility, icing, rain, hail, and turbulence.

Studies of the flight conditions and solutions of the traffic control problems caused by these flight conditions have been under way for a number of years. The NASA has been particularly active in turbulence aspects of the problem because of its importance to the structural design problem of airplanes as well as traffic control problems. The purpose of this paper is to review some of the recent atmospheric turbulence measurements and airplane response measurements obtained generally in thunderstorms at approximately 40,000 feet altitude.

This review will consist of the description of the airflow in the clouds, the spectral description of the atmospheric turbulence, and an indication of the response of the airplanes to the turbulence. The response of the airplane is of concern to all personnel connected with the flight, such as the air traffic controller, the crew, passengers, etc. The selected responses to be presented are the altitude deviations which are of special interest to the traffic controller in maintaining proper aircraft separation; the center-of-gravity accelerations, which give an indication of structural loads and passenger distress; and the attitudes, pitch, yaw, and roll, which give an indication of the pilot control problem.

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Airplane Flights in Atmospheric Turbulence and Evaluation of Data

An F-86 jet airplane was used to measure turbulence in cumulus clouds at altitudes of about 15,000 feet near Langley Air Force Base, Virginia. Other jet airplanes were used to obtain measurements in the severe turbulence in thunderstorms to altitudes of 40,000 feet over the southwest United States. The latter measurements were made during flight operations of the Weather Bureau National Severe Storms Project by aircraft instrumented by the NASA and operated by the Air Force. A T-33 airplane was used in the spring of 1960. An F-106 airplane was flown at high subsonic and low supersonic speeds through storms in the spring of 1961. The flights were made under the control of an FAA controller by use of radar equipment.

During the past decade, interest has attached itself to the description of atmospheric turbulence as a continuous (rather than discrete) process and to the use of spectra in the analysis of gust velocities and dynamic response of aircraft (ref. 1). In the evaluation of the turbulence, the time history of the vertical component of gust velocity is obtained from flight measurements of local angle of attack by means of a flow vane or differential pressure probe on a boom ahead of the airplane with due account taken for airplane motion. The time history is analyzed to determine the autocorrelation function and the power spectrum by numerical techniques (refs. 1 to 3) involving some 2,000 readings per record (100 seconds). The airplane responses presented in this paper, are evaluations from the time histories of the airplane motions to give the proportion of time that a given value is exceeded.

Time Histories of Gust Components

The nature of the turbulent flow within a cloud may be indicated by examining some time histories of the vertical and lateral components of the turbulence and by considering the statistical parameters of the turbulence. Some time histories will be considered first.

The time histories of two components of the true gust velocities for a traverse through a storm at 39,000 feet altitude are given in figure 1. The vertical components are shown in the upper trace and the horizontal components in the lower trace. For the vertical components a positive gust is up, and the positive lateral component is airflow toward the right of the airplane. In each case the velocities are plotted against time and distance. The time of cloud entry and cloud exit is indicated in the figure. It is noted that the time history of vertical component begins and ends at approximately -20 feet per second and the lateral component appears to have a linear trend from -70 fps to

+10 fps. Neither of these beginning and end points may be real since such factors as gyro drift and the inability to establish initial and final conditions prohibit the exact location of the zero value and the elimination of very low-frequency trends. The numerical values cannot be taken, therefore, as absolute values, although in this paper the values plotted will be quoted.

The similarity of the two components in figure 1 is rather impressive, especially at 50 seconds where large changes in the velocities occur in both the lateral and vertical components. This is the only case in the measurements made during the project in which such severe and sharp discontinuities occurred in both vertical and lateral components. Under such conditions, large airplane accelerations or motions might be expected; a change of 2.5g was experienced in this instance with an accompanying change of 20 fps in the airplane vertical velocity.

The characteristic of the flow of major interest is the irregular nature of the velocity fluctuations. In the traverse shown in figure 1, the wavelengths vary from large-scale disturbances of two miles or more in extent to short wavelengths of possibly 100 feet. Large-scale and perhaps persistent vertical motions appeared to exist within the storm, downward velocities near the edges of the cloud and large upward velocities near the center. Superimposed on these large-scale motions were short wavelength gust velocities. The airplane response thus consists of a random sequence of sharp accelerations and longer period displacements. It also appears, since the lateral components were large, that significant horizontal as well as vertical velocities were present within the storm.

Time histories of the flow in the storms actually exhibit a variety of characteristics. The flow apparently changes drastically, probably both in direction and velocity from development to decay and possibly from storm to storm. In figure 2, time histories in portions of three additional clouds are given. The first time history (fig. 2(a)) was taken from the midportion of a cloud traverse and shows large upward and downward velocities in the center of a cloud over a distance of approximately 5 miles. The lateral component shows similar characteristics. The second time history (fig. 2(b)) shows relatively light turbulence in the center of a traverse with no large-scale motions being present. The third time history (fig. 2(c)) shows an extremely large upward velocity of perhaps 200 fps with a width of $2\frac{1}{2}$ miles. Fairly low-intensity downward velocities occurred on each side of the large up-current. The lateral component shows large-scale currents of lower velocities. The random type of short wavelength turbulence imposes large loads on the airplane while the longer wavelength disturbances may produce smaller loads but large displacements of the aircraft. At the time of the positive gust velocity of 200 fps, the airplane was in a pitched-down attitude of 13° and had an upward vertical velocity of 83 fps. The vertical acceleration of the airplane at this instant, however, was only 18 fps^2. Incidentally, severe hail was encountered within the third storm, leading to loss of the sideslip vane, as noted in figure 2(c), and to significant hail damage on the airplane.

It would appear from the preceding discussion that the internal structure of thunderstorms may be irregular and strongly cellular (figs. 2(a) and 2(c)), or relatively weak with no cellular development (fig. 2(b)). Under these conditions, the type and location of turbulence within the visible reaches of the clouds would probably be impossible to predict by the pilot entering the cloud. Assistance in avoiding regions of severe turbulence as a part of traffic control would of necessity come from surveillance radar.

Spectral Representation of Turbulence

The intensity of the turbulence for a given traverse or patch of turbulence may be described through power-spectral representation. The spectra of turbulence for average clear-air turbulence conditions, turbulence in cumulus clouds, and turbulence in severe storms are shown in figure 3. The power $\phi(\Omega)$ is plotted against reduced frequency in radians per foot and wavelength λ in feet. A logarithmic scale is used in each case. The least severe turbulence is shown by the lower curve and the most severe turbulence appears as the upper curve. The square roots of the areas under these spectra are the root-mean-square (rms) gust velocities, a measure of the turbulence intensity.

The rms values vary considerably for different traverses through a given type of turbulence. The rms gust velocities for the spectra in figure 3 are 3.48, 6.14, and 13.77 fps for the samples of clear air, cumulus cloud, and thunderstorm turbulence, respectively. The rms gust velocities for traverses through thunderstorms varied from 6.14 to 16.02 fps. The rms gust velocities for nine traverses through cumulus clouds varied from 3.4 to 9.2 fps. The values of rms gust velocity cited for thunderstorms apply to altitudes from approximately 20,000 feet to 40,000 feet. The values for cumulus clouds apply to altitudes between 10,000 and 20,000 feet, while the value for clear air is for an altitude below 5,000 feet.

It might be noted from figure 3 that the spectra all cover a range of wavelengths from about 3,600 feet to 60 feet, or 1/6 to 10 cps. Some flights made at supersonic speeds have extended a few spectra to wavelengths of approximately 14,000 feet and indicate that these spectra for thunderstorm turbulence continue as an approximate straight line on the logarithmic scales to the longer (14,000 feet) wavelengths. These are the wavelengths to which the supersonic transport will respond.

These data have indicated that the spectra are of the same shape for the different weather conditions, the power decreases proportionally to (frequency)$^{-5/3}$ for the higher frequencies, and for the thunderstorm turbulence the scale of turbulence is of the order of several thousand feet (3,000 to possibly 5,000 feet).

Variation Within Clouds

Although it was intended that several traverses be made through a cloud on identical tracks at a given altitude or displaced vertically from a given track for an altitude survey, it was not possible to follow this procedure during the operations of the National Severe Storms Project because of changes in the radar echo with time and the difficulty of positioning the aircraft in the storm. The time or altitude survey may be influenced by positioning variations and time differences for the altitude survey.

The results showing the variation in the intensity of turbulence with time for one storm (at 39,000 feet altitude) are given in the left side of figure 4. The intensity of the turbulence is given by the rms value plotted against the time from the start of the first traverse. Also shown is the cloud diameter. The figure shows that the cloud was growing during two periods (0 to 5 minutes and at approximately 30 minutes) during which time the intensity of turbulence was relatively severe ($\sigma = 15$ fps).

The right-hand part of figure 4 summarizes the intensity of turbulence versus altitude. This cloud survey was made on approximately east and west headings with each traverse being approximately 20 to 30 nautical miles in length. For the penetrations made, the most severe turbulence occurred at the highest altitude, 40,000 feet, with relatively constant but less severe turbulence at the lower altitudes. The rms values are 9.73, 6.64, 6.14, and 6.48 fps for the highest to the lowest altitudes, respectively. The last traverse at the lowest altitude started 35 minutes after the beginning of the first traverse.

The preceding samples indicate that the intensity of turbulence varies considerably from storm to storm and even within different portions of a given storm. In general, it does not appear that the pilot can estimate such variations in storm intensities or control difficulties prior to entering a storm area without the assistance of radar surveillance.

Airplane Response Within Storms

Now let us consider some of the measured airplane motions and their implications in regard to piloting difficulty or passenger comfort in flight through storms. A quantity of particular interest to the airways traffic controller is airplane vertical displacement or altitude; for passenger comfort, as well as loads, the normal acceleration is of more concern. The three attitude displacements, pitch, roll, and yaw, are given as an indication of the piloting difficulties.

For traffic control purposes the altitude variation from the assigned altitude is probably the most important displacement to consider. Bands covering the distributions of the measured altitude deviations are shown in the upper portion of figure 5 for several traverses through storm areas. The portion of time that a given deviation from the assigned altitude is exceeded is indicated. This deviation may be either above or below the assigned altitude, although an examination of the altitude time histories indicated that in the majority of the traverses the T-33 airplane lost altitude while the F-106 airplane gained altitude.

It is noted from figure 5 that the aircraft may be at least 500 feet from the assigned pressure altitude from about 5 to 60 percent of the time. (The pilot was instructed to correct for only relatively large changes in attitude. The test airplanes were relatively rigid with good stability characteristics.) In one instance, the airplane was as much as 4,000 feet from the assigned altitude. The reason for such large deviations is not known but this aircraft consistently climbed during the traverses and, in two cases, altitude changes of several thousand feet occurred.

For comparison with these storm data, data from routine operations on the airlines are included in figure 5. It is apparent that for routine airline operations the frequency of occurrence of 500-foot altitude deviations is about 1/1,000 to 1/10,000 as frequent as the deviations in a thunderstorm. It is interesting to note that this ratio is roughly equal to the percent of flight distance in storm turbulence experienced by the airlines (ref. 4).

If the data from the storm penetrations are adjusted to account for the amount of clear-air flight time in routine airline operations, the agreement between altitude deviations for thunderstorm flights and commercial operations is very good, as shown by the lower shaded area in figure 5.

The next four figures show the percent of time that given values of normal acceleration, pitch attitude, yaw attitude, and roll attitude, respectively, were exceeded by the two test airplanes in thunderstorms. The normal accelerations are presented in figure 6. This quantity is usually the major factor influencing the pilot's or passenger's judgment of the intensity of the turbulence. Since the accelerations depend on airspeed, weight, etc., it is not possible to transfer these accelerations directly to another aircraft. For the test aircraft, an acceleration increment of 0.5g would be exceeded between 0.1 to 0.4 of the time for the 1 to 5 minutes involved in the individual traverses. Relatively large accelerations of 1.5g would be exceeded 0.001 of the time on some of the flights. Transports do not intentionally fly through the type of turbulence represented here, except as an absolute necessity. In this connection, VGH-type records show that in routine flights an acceleration increment of about 1.5g is experienced on the order of once in 10,000,000 miles of flight (ref. 5). One such experience probably occurred on May 6, 1963, when a Trans-Canada Airlines Flight of a Vanguard airplane (as reported in the newspapers) encountered 10 seconds of turbulence at 21,000 feet altitude over the Rocky Mountains. Large altitude losses and vertical accelerations were reported.

An examination of pitch, yaw, and roll angles in figures 7, 8, and 9 indicates that pitch and yaw were about the same magnitude and frequency, with roll attitude being of larger magnitudes. For pitch and yaw, angles of 0.12 radian (approximately 7^{o}) were exceeded about 1 percent of the time, as compared to 0.2 radian (12^{o}) for roll attitude. Although not shown in the figure, roll angles as large as 0.5 radian (about 30^{o}) were experienced upon occasion. In all the traverses investigated, the airplane equipped with the yaw and pitch dampers (supersonic airplane) experienced the smaller roll angles of the two test airplanes.

A final word of caution: These data on airplane response pertain to a trainer and fighter type of aircraft of two radically different designs. The trainer is a straight-wing subsonic aircraft and the fighter is a heavy delta-wing airplane capable of supersonic speeds. The motions can only be applied roughly to other aircraft (e.g., large bombers or transport) if proper adjustment of the data is made for the differences in aircraft characteristics.

Concluding Remarks

The preceding discussion was directed toward the effect of atmospheric turbulence, especially the turbulence in severe storms, on air traffic control. The measurements of turbulence within storms point out that the internal structure of thunderstorms may be irregular and strongly cellular, or weak with no cellular development. Under these flight conditions, altitude variations of at least 1,000 feet and rather severe vertical accelerations were recorded. For the aircraft flown, roll angles up to 0.5 radian were experienced while the yaw and pitch were of smaller magnitudes, being of the order of 0.1 to 0.2 radian.

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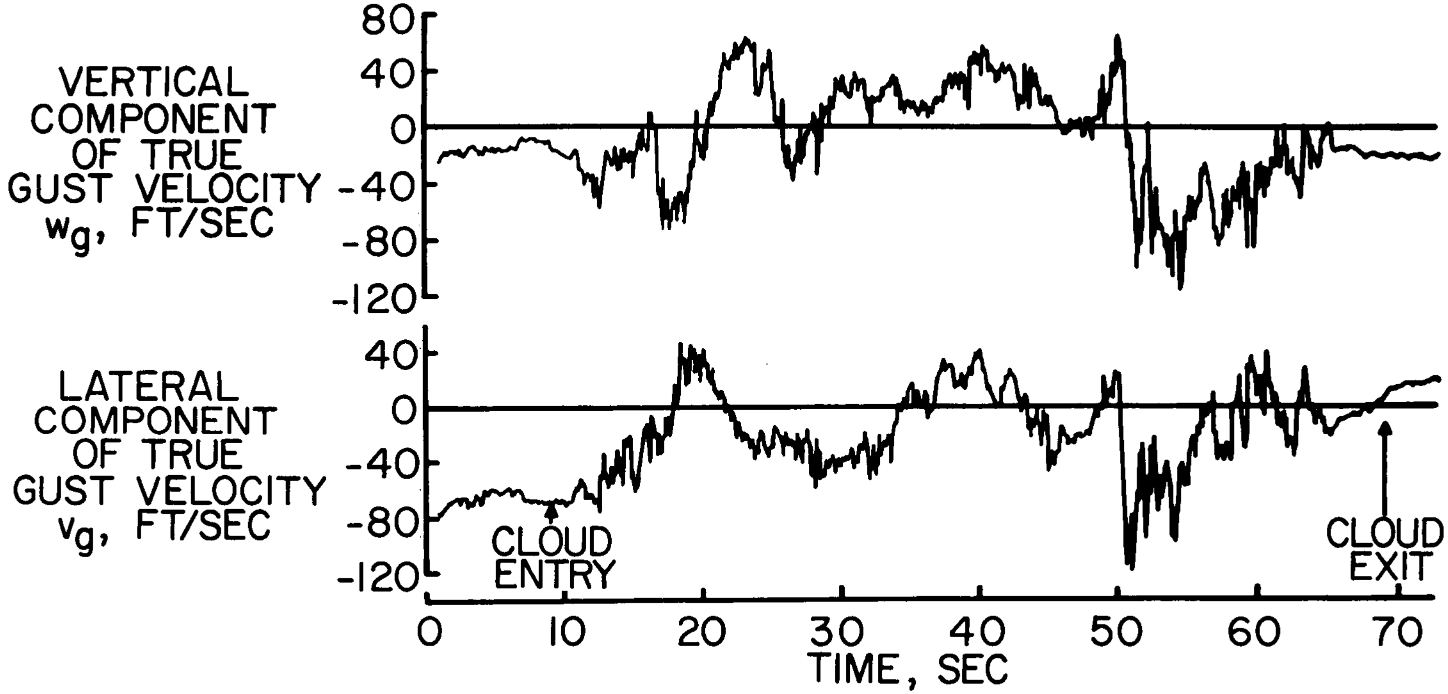

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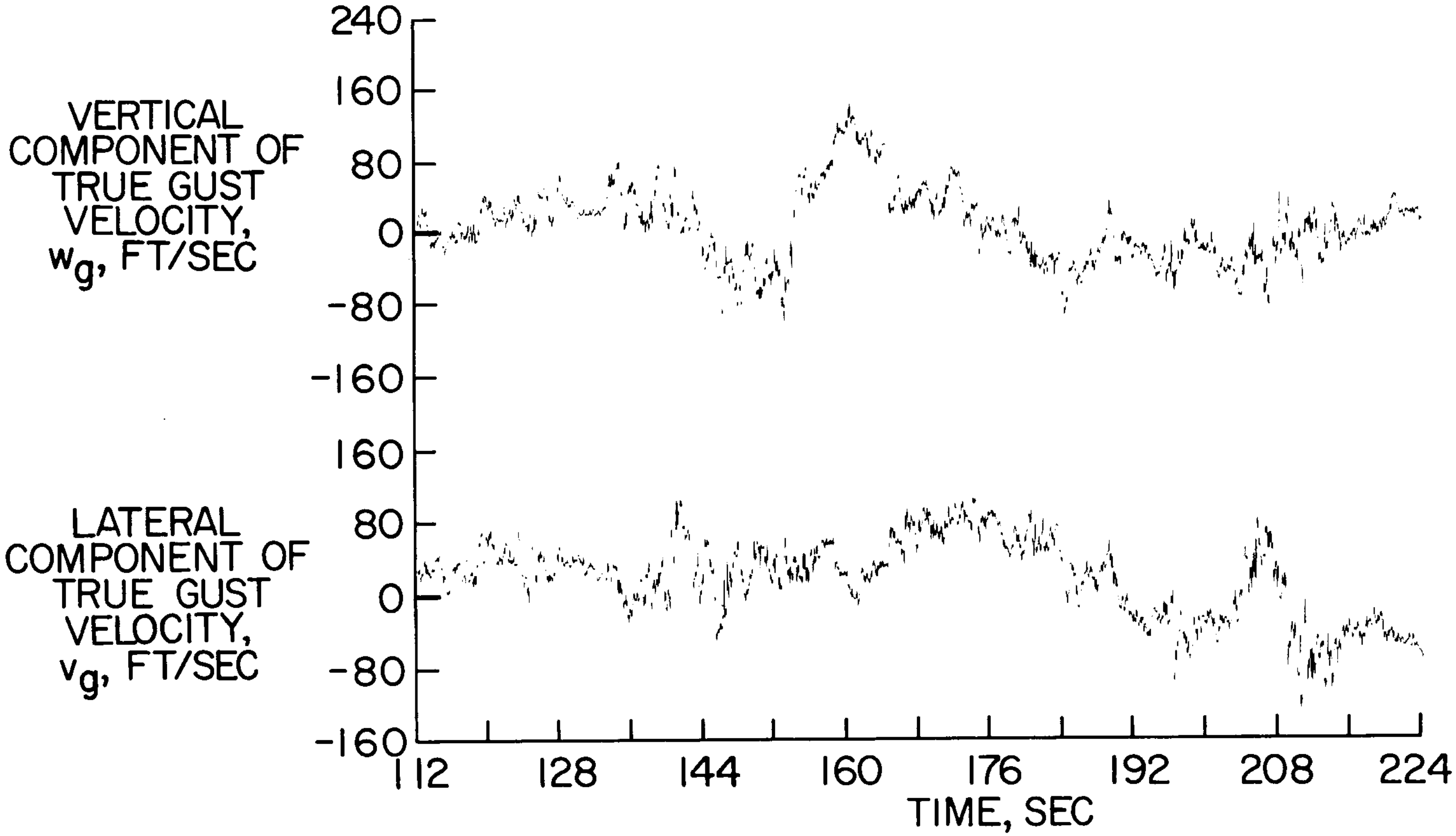
Figure 1.- Time histories of vertical and lateral components of true gust velocity for a thunderstorm traverse at 39,000 feet altitude, May 17, 1960.



(a) 38,000 feet altitude, May 16, 1960.

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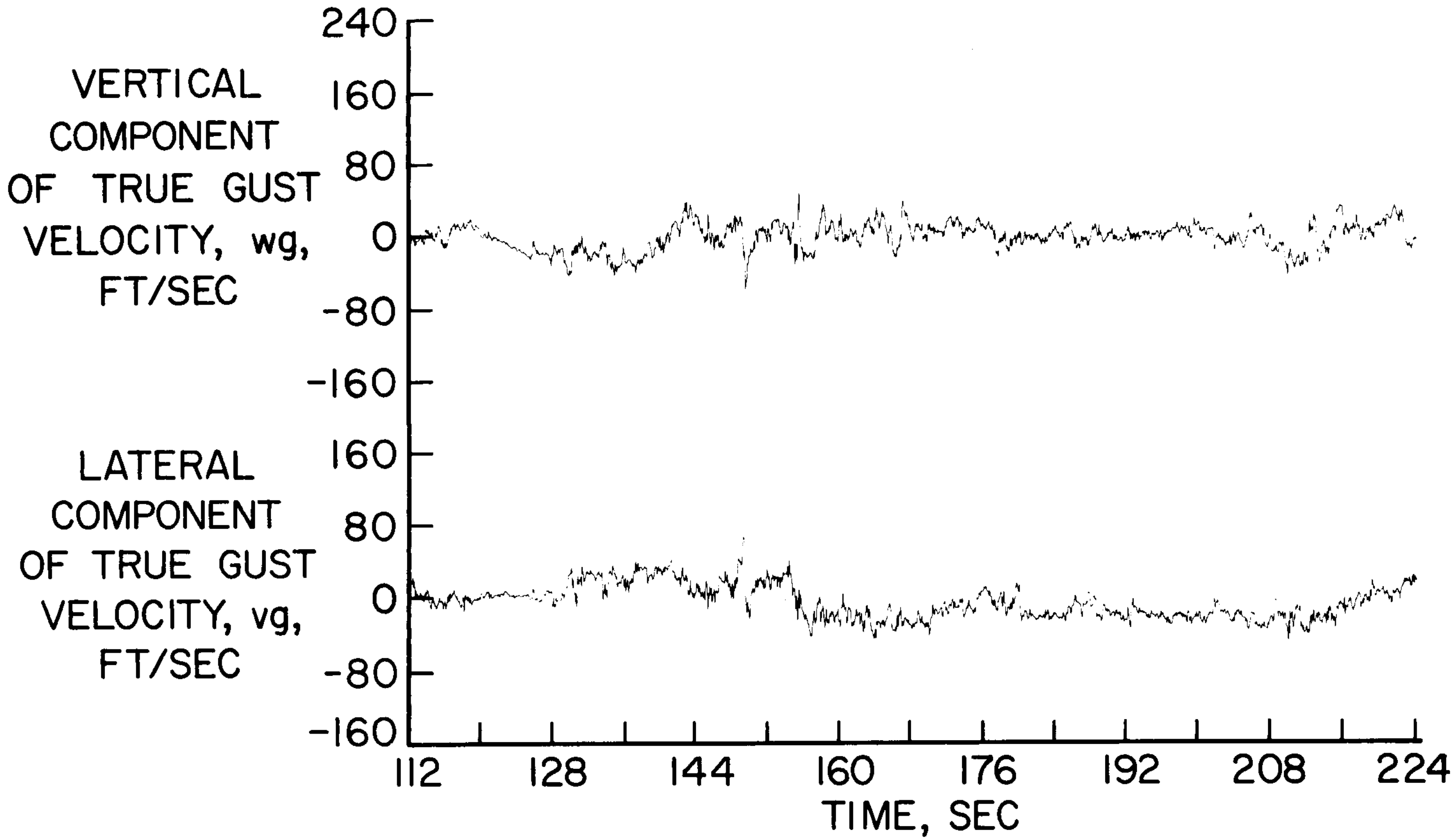
Figure 2.- Time histories of gust velocities in portions of three additional storms.



(b) 40,000 feet altitude, May 4, 1960.

Figure 2.- Continued.

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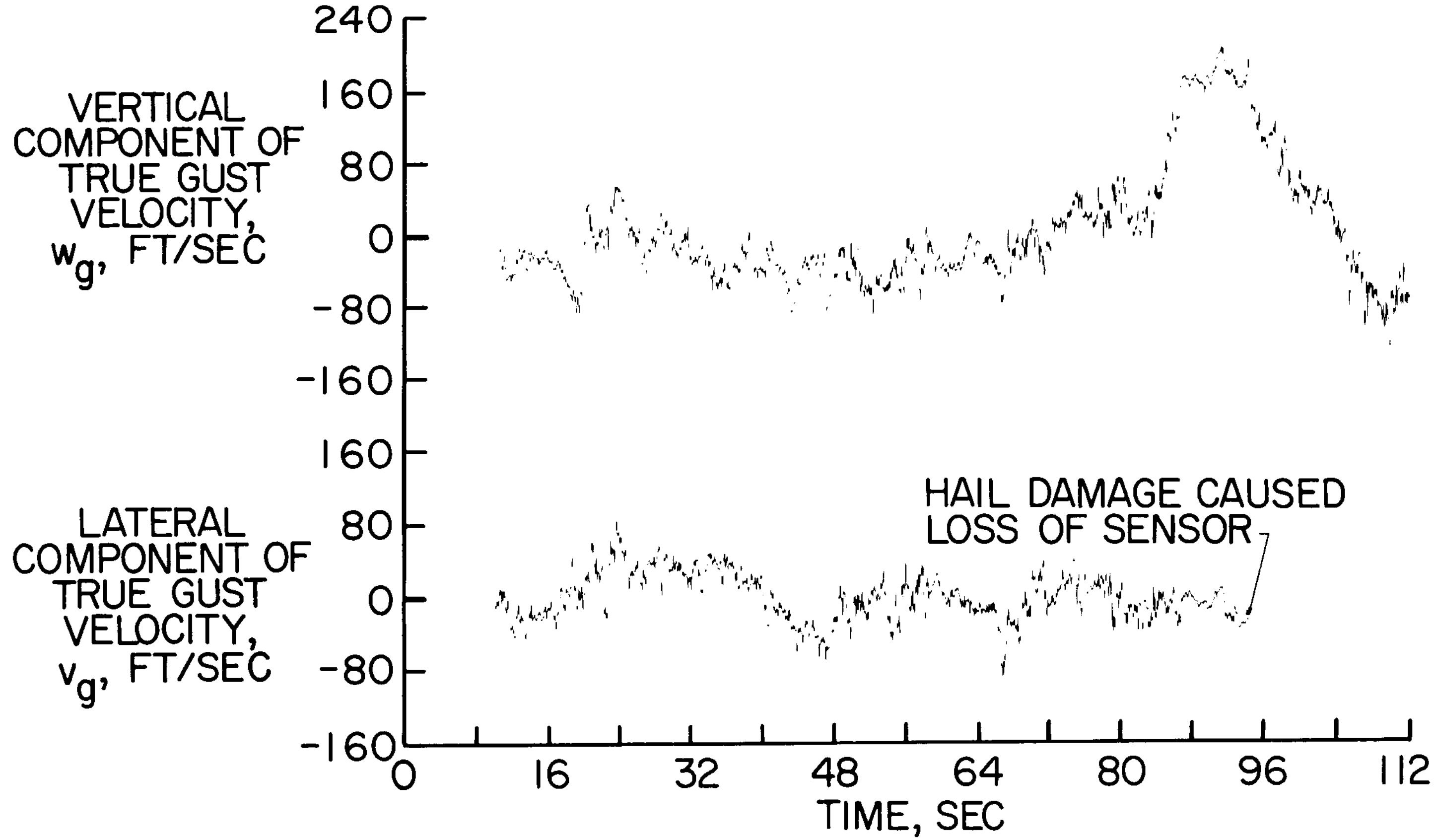

(c) 40,000 feet altitude, May 16, 1960.

Figure 2.- Concluded.

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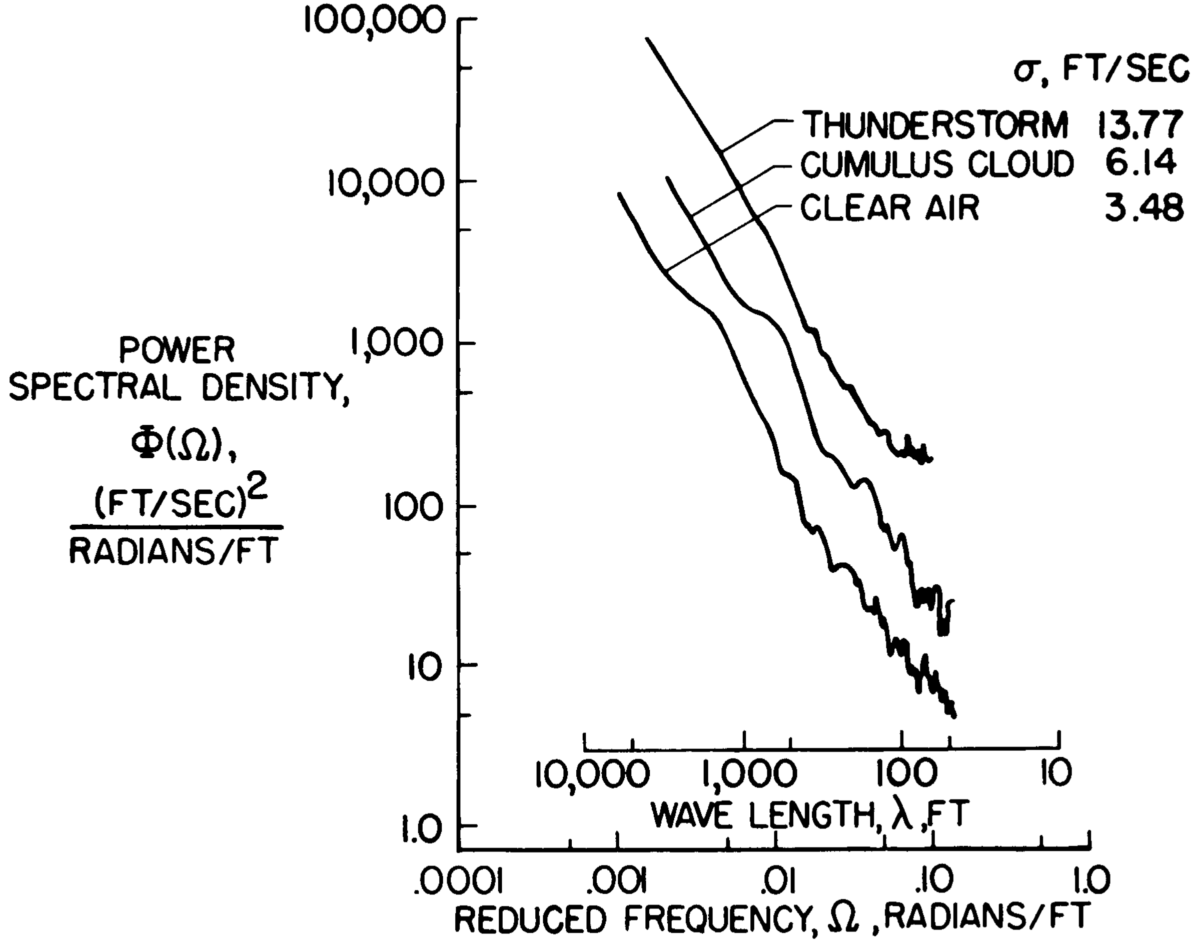

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Figure 3.- Typical power spectra of turbulence for three weather conditions.

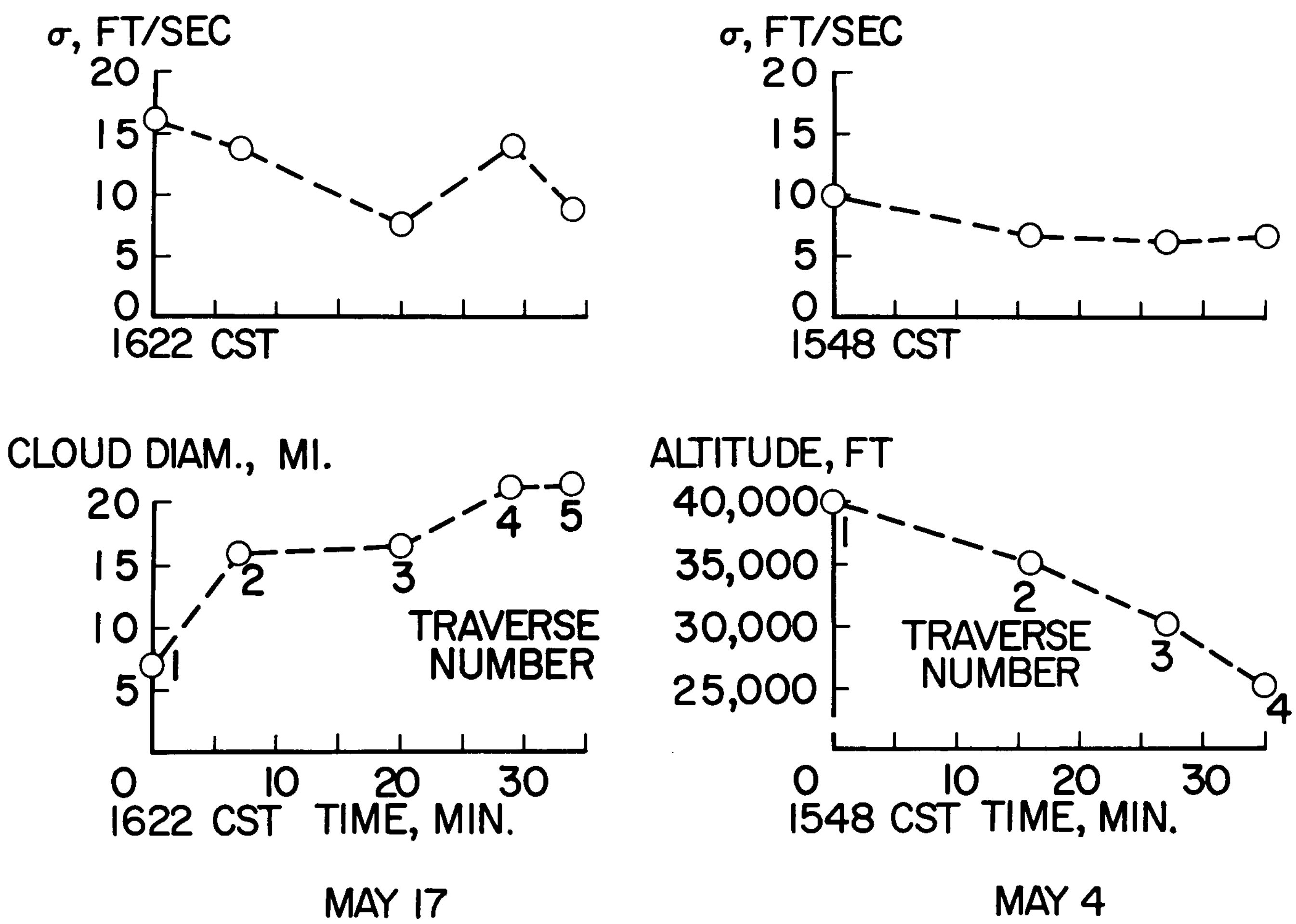

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Figure 4.- Turbulence intensities for different times at a given altitude (39,000 ft) and for different altitudes.

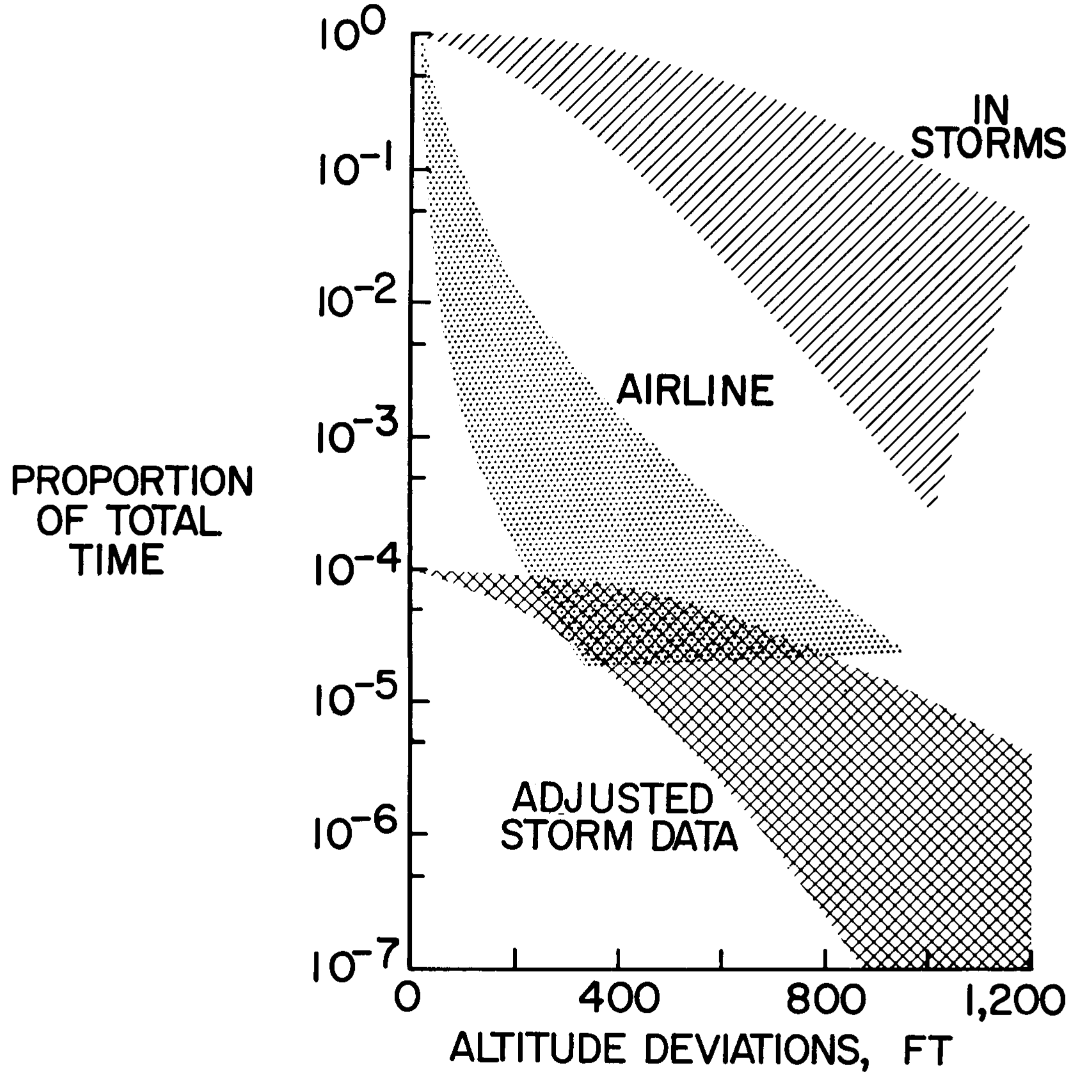

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Figure 5.- Altitude deviations from assigned altitude.

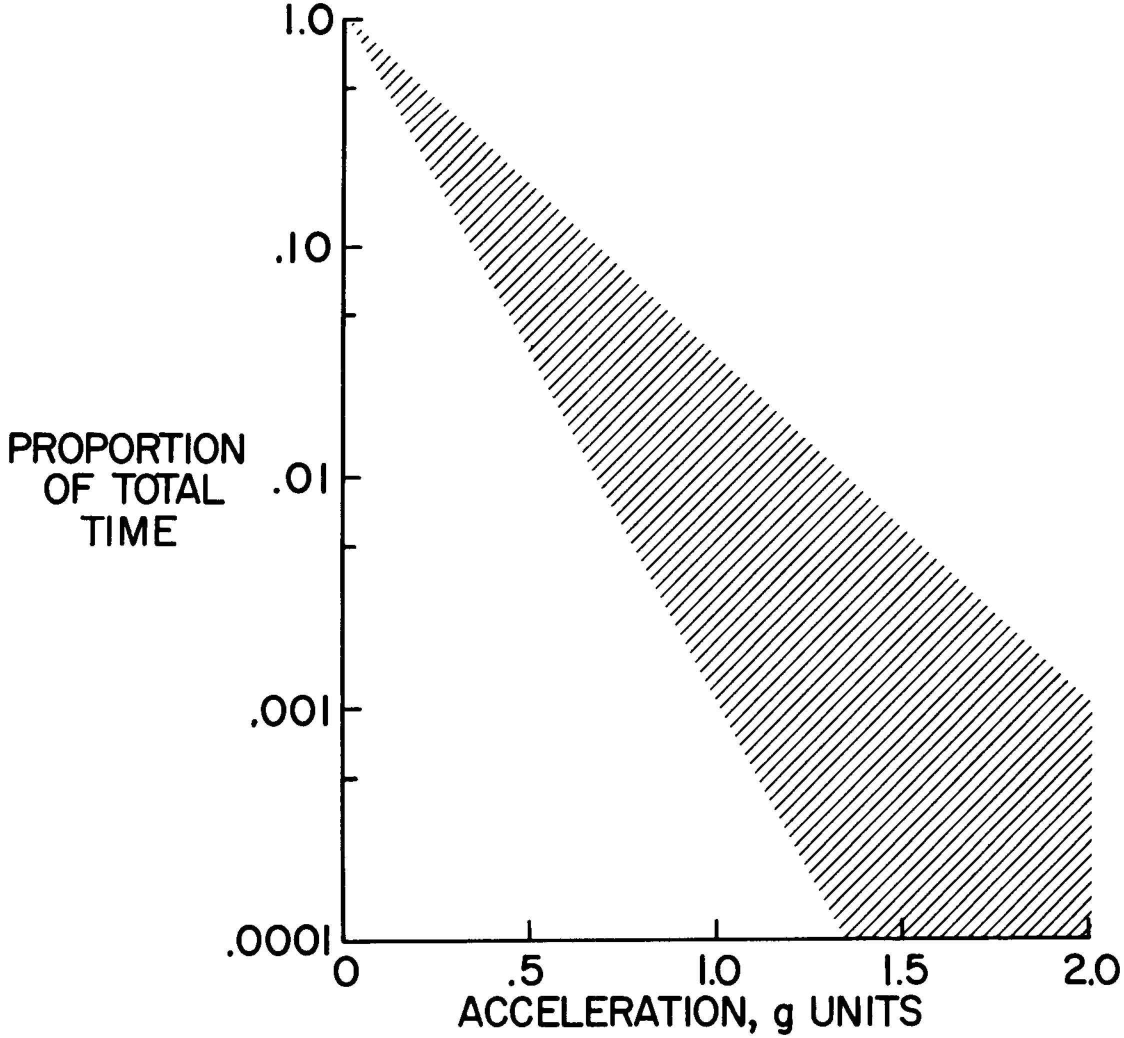

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Figure 6.- Accelerations experienced during flights through thunderstorms.

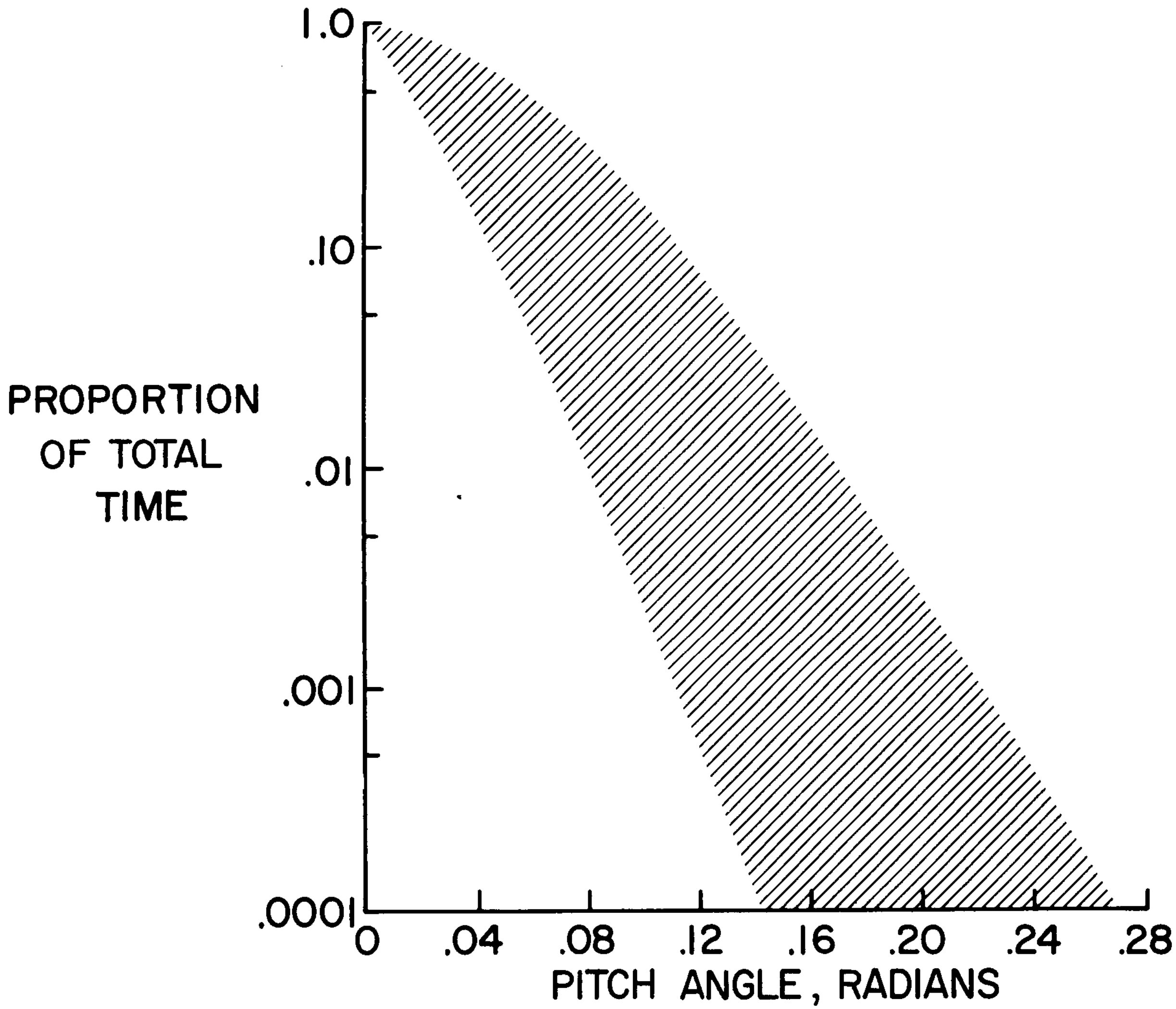

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Figure 7.- Pitch attitude experience in flights through thunderstorms.

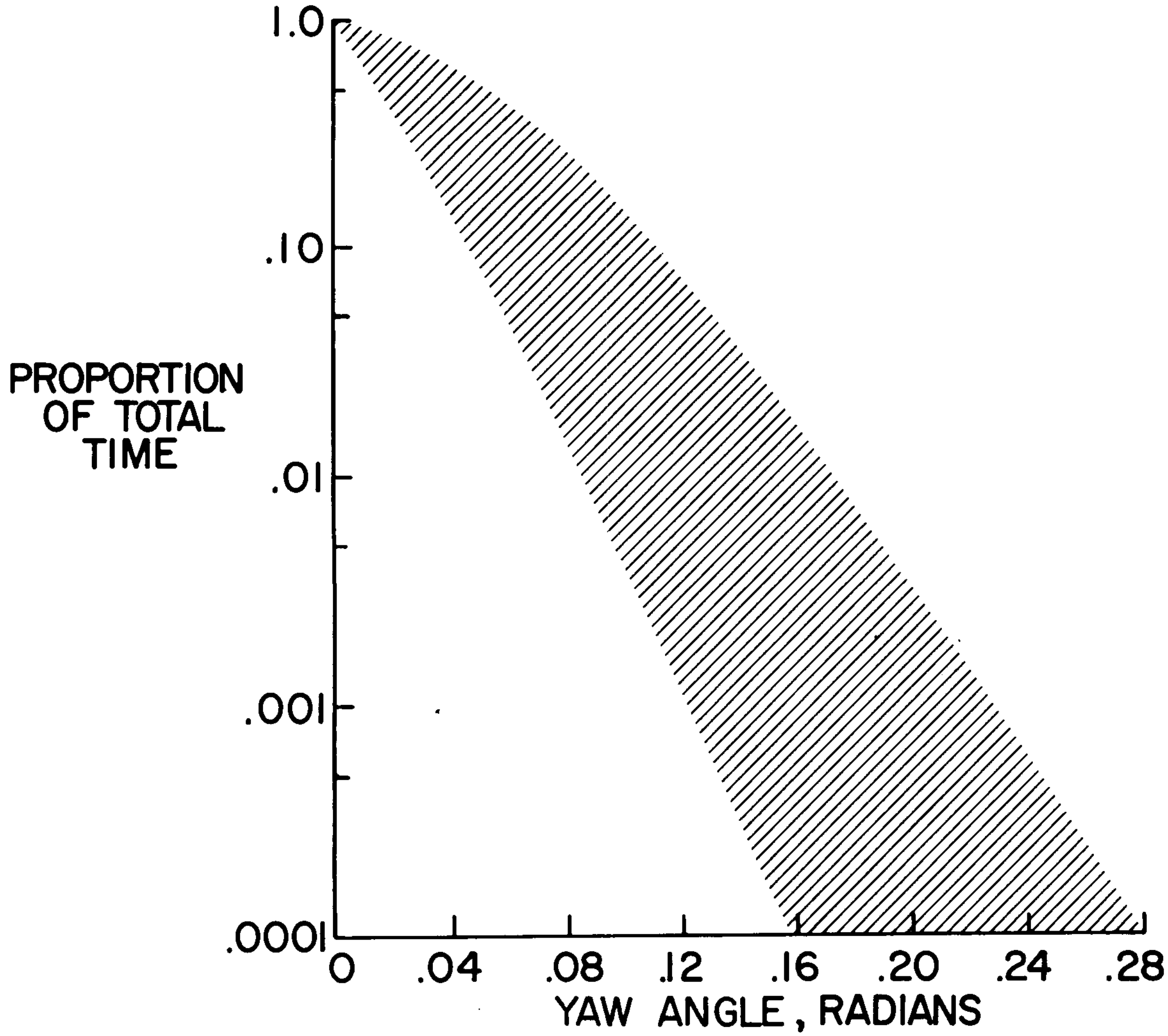

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Figure 8.- Yaw attitude experience in flights through thunderstorms.

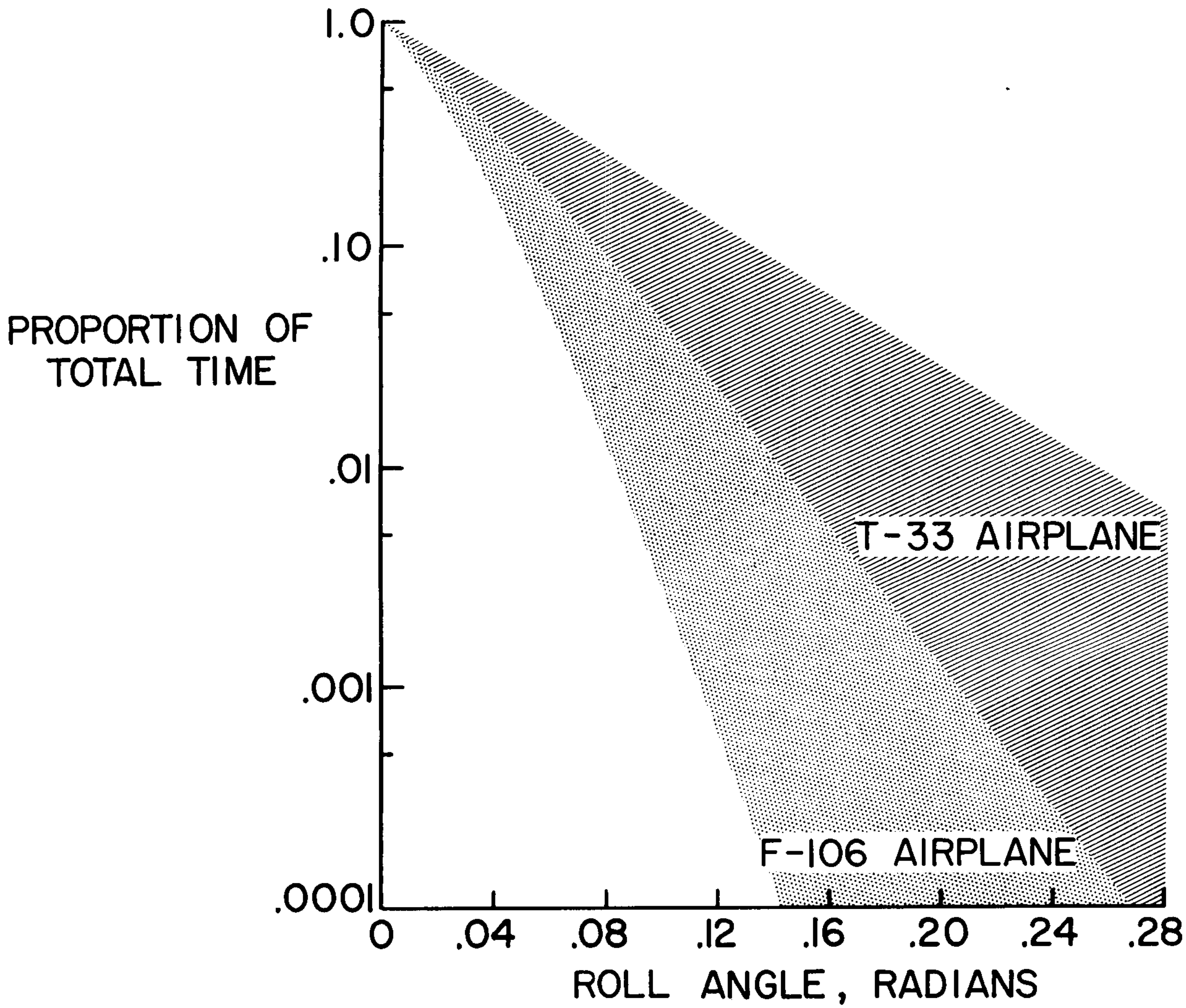

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Figure 9.- Roll attitude experience in flights through thunderstorms.